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14. ABSTRACT
This study focused on understanding how advection of density within the bottom boundary layer influence the three-dimensional structure, evolution, and dynamics of both the bottom boundary layer and the overlying (interior) flow. Simple theories were developed and then tested and extended using both a numerical model and analysis of oceanic observations. Results indicate the simple theories are relevant to the ocean and that the bottom boundary layer plays an important role in the behavior of ocean currents, even when the boundary layer is thin compared to the current depth.

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Final Report

Three-Dimensional Adjustment of Stratified Flow Over a Sloping Bottom

ONR Grant No. N00014-97-1-0161
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Long-Term Goals

Our ultimate goal is to understand the dynamics of low-frequency ocean currents flowing over variable topography and the role of the bottom boundary layer in steering and modifying such currents.

Objectives

Our specific objective was to understand how advection of density within the bottom boundary layer influences the three-dimensional structure, evolution, and dynamics of both the bottom boundary layer and the overlying (interior) flow.

Approach

Our approach consisted of a combination of theoretical modeling, process-oriented numerical modeling, and observational analyses. This study was based on the notion that the adjustment of stratified ocean currents flowing along sloping topography involves a feedback between the bottom boundary layer and the overlying current. The overlying current produces a bottom stress that causes the bottom boundary layer to grow. The bottom boundary layer flow advects buoyancy across isobaths, creating vertical shears that reduce bottom stress and ultimately halt both the growth of the bottom boundary layer and the adjustment of the overlying flow. In some sense, the overlying current is 'controlled' by the bottom boundary layer.

Tasks Completed

We developed an idealized semi-analytical model of the adjustment of a stratified flow over a sloping bottom that provides considerable insight into the structure, evolution, and dynamics of both the bottom boundary layer and the overlying (interior) flow (Chapman and Lentz, 1997).

We collected and analyzed existing, long-term, moored current observations along the west coast of the U.S. and showed that the near-bottom flow and hence the bottom stress are reduced due to adjustment of the near-bottom density field (Lentz and Trowbridge, 2000).

We completed a thorough study of the adjustment of a narrow along-isobath current over a uniformly sloping bottom using a numerical model (Chapman, 2000), both to understand the dynamics and to compare with our previous idealized semi-analytical model of such a flow (Chapman and Lentz, 1997).

To understand the relative roles of frictional spindown and buoyancy shutdown, we completed a theoretical and numerical modeling study of the deceleration of a finite-width, along-isobath current over a uniformly sloping bottom (Chapman, 2001),

Results

Our idealized semi-analytical model of the adjustment of a stratified flow over a sloping bottom (Chapman and Lentz, 1997) suggests that an equilibrium can be achieved in which both the bottom boundary layer and the overlying current adjust through feedback mechanisms such that the bottom stress is reduced to zero everywhere. The current can then continue unimpeded by bottom friction. This simple idea provides a potential explanation for how oceanic slope currents in contact with the bottom can flow long distances without spinning down due to bottom friction.

A numerical modeling study to evaluate and extend out idealized semi-analytic model produced qualitatively similar results. In the numerical model, a narrow, stratified, cyclonic along-isobath current over a uniformly sloping bottom generates a bottom Ekman layer immediately downstream of its origin, with downslope transport everywhere beneath the current, carrying lighter water under heavier water to produce a vertically well-mixed bottom boundary layer. At the top of the boundary layer, Ekman suction on the shallow side and pumping on the deep side lead to density advection in the vertical, tilted interior isopycnals, and thermal-wind shear of the interior along-isobath velocity. Flow above the bottom boundary layer is nearly perfectly geostrophic and along isopycnals. Buoyancy advection in the bottom boundary layer continues to cause growth of the boundary layer downstream, with subsequent reduction in bottom stress, until the flow reaches a steady downstream equilibrium beyond which only gradual changes occur as a result of viscosity and mixing.

The numerical results have been used to test some of the assumptions made in our idealized model (Chapman and Lentz, 1997). The same basic dynamics dominate, and some of the scales and parameter dependencies predicted by the idealized model apply to the numerical results. For example, the distance to the downstream equilibrium decreases with increasing buoyancy frequency and/or bottom slope, and the equilibrium structure is nearly independent of the bottom friction coefficient. The equilibrium bottom boundary layer thickness and the interior along-isobath velocity just above the boundary layer closely obey the idealized model scale; the boundary layer thickness decreases with increasing buoyancy frequency and is independent of bottom slope, and the overlying current decreases while its width increases as either the buoyancy frequency or bottom slope decreases. However, the interior vertical shear in the numerical model tends to decouple the overlying current from the bottom boundary layer, so the shape of the bottom boundary layer in the downstream equilibrium is different from the idealized model, and neither the current width nor the surface currents are as sensitive to parameter variations as the idealized model suggests. Finally, the along-isobath current is not geostrophic near the bottom of the bottom boundary layer, as assumed in the idealized model, so the bottom boundary layer is not fully arrested, i.e. bottom stress never quite vanishes downstream, suggesting that a completely frictionless downstream equilibrium is unlikely to be achieved.

Analytical solution to a theoretical model of a downwelling current suggests that buoyancy shutdown always reduces the deceleration time scale from that for frictional spindown alone and produces a non-zero steady along-isobath current overlying an arrested bottom mixed layer. The model is most sensitive to the Burger number $S = N\alpha/f$ where N is the buoyancy frequency, α the bottom slope, and f the Coriolis parameter. The steady state is reached more rapidly and the steady current is stronger with increasing S. Buoyancy shutdown remains important in the deceleration process even when its individual time scale for adjustment is an order of magnitude larger than the frictional spindown time scale. Results from a primitive-equation numerical model study generally support the theory. However, there is a weaker steady flow in the numerical model, especially with stronger stratification, because the theoretical model neglects the cross-isobath component of bottom stress and ignores vertical shears above the bottom mixed layer. Interior vertical shears tend to decouple the near surface flow from the bottom mixed layer, producing more spatially variable steady flows in the numerical model than in the theoretical model. Buoyancy shutdown is also important in the deceleration of upwelling currents, substantially reducing the time to reach steady state from that for frictional spindown alone. Details of both the deceleration and the steady state vary sharply with the turbulent closure scheme, so generalizations are difficult.

In collaboration with J. Trowbridge we examined existing observations to determine whether the structure and dynamics of the oceanic bottom boundary layer are consistent with our idealized model (Trowbridge and Lentz, 1998; Lentz and Trowbridge, 2000). Our analysis of existing current observations shows that fall and winter mean profiles from a mid-shelf site off northern California are very similar from year to year, particularly near the bottom (Lentz and Trowbridge, 2000). Mean profiles at several different locations along the northern California shelf also have similar vertical structure. Analysis of these observations indicates a reduction in the near-bottom flow consistent with our idealized model. Cross-shelf density gradients along the bottom balance the vertical shear in the alongshelf flow that reduces the near bottom flow to about 1 cm/s. This balance holds for time scales of a week or longer, consistent with theoretical estimates of the shutdown time for bottom stress which is approximately a week at this site. These results provide some of the first observational evidence for a reduction in the bottom stress due to adjustment of a stratified flow over a sloping bottom. There is also vertical shear in the cross-shelf flow which is too large to be balanced by friction and may be in thermal wind balance with an along-shelf density gradient. This is not consistent with our idealized model and may be a consequence of complex bathymetry.

Direct covariance estimates of bottom stress made on the New England shelf by J. Trowbridge, W. Shaw, and S. Williams (WHOI) and the associated drag coefficient are about an order of magnitude smaller than typically assumed over continental shelves. The small bottom stresses are apparently due to the smooth, featureless bottom at this site resulting in a small bottom drag coefficient, rather than buoyancy adjustment within the bottom boundary layer. Comparisons with other terms in the depth-averaged momentum balance suggests bottom stress is negligible, e.g. bottom stress is nearly a factor of ten smaller than the wind stress. Analysis of the bottom boundary layer dynamics indicates along-isobath bottom stress forces a weak cross-isobath transport, consistent with an Ekman balance. However, this stress-driven flow is only a small component of the near-bottom cross-isobath velocity structure.

Impact for Science

Our modeling and observational results suggest that the bottom boundary layer plays an important role in the behavior of ocean currents, even when the boundary layer is thin compared to the current depth. However, the numerical modeling results suggest that the coupling between the bottom boundary layer and overlying current may not be as strong as previously thought because of vertical shears that develop in the interior flow.

Relationships to Other Projects

We collaborated closely with J. Trowbridge to examine the character of the bottom boundary layer and the interior flow during previous studies, notably STRESS, and during the recent CMO field program to determine whether the structure and dynamics are consistent with our idealized model. We also collaborated with R. Pickart, who is examining the structure of the bottom boundary layer beneath the Deep Western Boundary Current.

We worked closely with Glen Gawarkiewicz who is leading a field program in the South China Sea, as part of the ONR sponsored ASIAEX program. Many of the ideas and results from our modeling studies have applications in that region.

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